Precicion-made SKF MR Steel for transmission components

Archives Technical report

PRECISION-MADE SKF MR STEEL FOR TRANSMISSION COMPONENTS

Ovako has an extensive R&D since many years, an area that now is in an even higher intensity. Some of the R&D work is published in our technical reports.

Due to that Ovako of today has had a number of different company names and used various trade marks we have until now chosen to not have these reports publicly available. However, many of these technical reports contain valid data about material and steel grades that we still promote, but with other names etc

The following Technical Report from 1985 is about the roots of steel making in Ovako, describing properties and benefits using steel from Ovako in transmission components.

Data and processes in this report represent state of art at time of publishing. If not the exact data, at least the principles are in many cases still used and valid. Where data has been further developed. For our updated description see our home page section; https://www.ovako.com/en/industry-solutions/light-and-heavy-vehicles/powertrain/

In this Technical Report there is used the following Company names and trade marks that no longer is used by Ovako AB.

SKF Steel; This company name is no longer used. The organization is now part of Ovako AB.

Technical Report 1/1985

Precision-made SKF MR steel for transmission components

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SKF Steel

Abstract

Automotive applications in general, and transmission components in particular, put stringent demands on the raw materials used.
The flexibility and the precision of the SKF MR steelmaking process make this process uniquely well suited to meet requirements on high quality and high consistency.
This article reviews recent developments as regards control of non-metallic inclusions, fatigue resistance, machinability and hardenability of steels used in transmission applications.

Introduction

Transmission components are produced in large series to strict tolerances.
Two operations are of primary importance to the manufacturing cost, the soft forming (forging and/or machining) and heat treatment.
The demands on the finished products are high, as transmission components are mostly subjected to high stresses and component life must be long.
For SKF Steel, this combined demand for high endurance and good manufacturing economy has been a guideline in steel development ever since rolling bearing steel became part of the product program in the early 1900's.
Rolling bearings and gears have many points in common, and this is especially true of the demands made on the steel.
The SKF MR process was designed and developed to provide highly consistent steel of high quality for high-quality products.
The SKF MR process is described in detail in references (1) and (2).
The use of the SKF MR process for rolling bearing applications is discussed in (2), and steel developments for one automotive application, valve springs, is detailed in (3).
A summary of the requirements for steels for transmission components has already been published by SKF Steel (4).
This article gives a general introduction to the developments carried out at SKF Steel in the field of transmission component steels, and outlines the fundamentals of steelmaking, machinability and fatigue required to optimize transmission component manufacture and performance.

Demands on Transmission Steel

The main demands on steel for transmission components can be summarized under three headings:

— Fatigue resistance
— Machinability
— Hardenability

The Fatigue resistance of the steel used must be high and consistent. In particular, the component reliability, i e the frequency of early failures, must be extremely low.

Machinability must be good and consistent, as much of the manufacturing cost in transmission component production is incurred in this process.

Hardenability must be consistent and predictable. Case hardening is a complex process, and the distortions caused by heat treatment must be kept to a minimum and must be consistent to enhance productivity. The result of the case hardening also affects the product properties.

Precise and Flexible Steelmaking

A universal requirement of high-quality steel is the capacity to meet strict demands with high precision.

The SKF MR process is eminently suited to do so. SKF MR is a two-stage process, where the initial stage (M for melting) encompasses melting of the charged scrap and sponge iron in an SKF twin-shell furnace.

In the second stage (R for refining), the steel melt is deoxidized, alloyed and temperature adjusted in an ASEA-SKF ladle furnace.

The finished steel is uphill teemed to ingots which are then rolled into billets. After billet conditioning, rolling to end products commences. SKF Steel produces seamless tubes, bars, rolled or forged rings, wire rod and drawn wire in a large number of steel grades.

The quality-critical part of the steelmaking process is the ladle furnace treatment.

The basic operations that can be performed in the ladle furnace are outlined in Fig. 1.

Deoxidation

The deoxidation process serves to remove oxygen from the steel melt. Oxygen present in the steel melt will form oxide inclusions on solidification, and there is a direct relationship between oxygen content and the amount of oxide type inclusions in the finished steel.

At SKF Steel deoxidation is normally achieved by precipitation, which is induced by the formation of alumina oxides, and inclusion removal by inductive stirring.

The ASEA-SKF ladle furnace also has facilities for heating, argon gas stirring and vacuum treatment. The deoxidation process is largely a function of time, *Fig 2,* and investigations have shown (2) that inductive stirring provides very effective inclusion removal.

A very low content of oxygen, and thus oxide type inclusions, forms the basis of the fatigue characteristics of SKF MR steel.

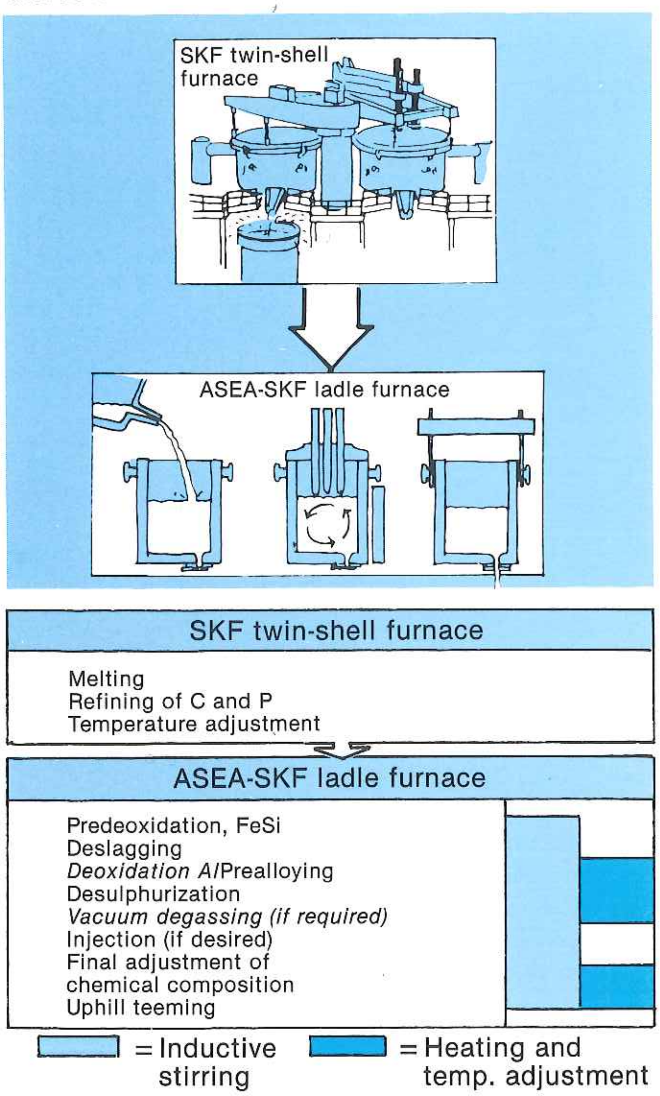

Fig. 1. Manufacturing procedure in the SKF MR process.

Sulphur content adjustment

The sulphur content of the steel can be adjusted to narrow limits at any desired level during refining.

The role of sulphur in steel is discussed in more detail below.

Today, variants of SKF MR steel are produced with maximum sulphur contens of 0.005% S, as well as high sulphur variants with sulphur contents of about 0.060% S.

Regardless of the desired sulphur content the SKF MR process can meet the requirements with high precision.

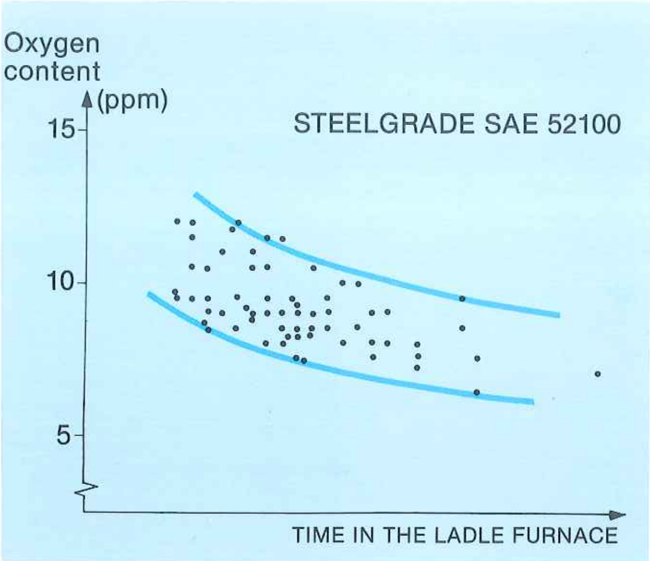

Fig. 2. Oxygen content versus time in the ASEA-SKF ladle furnace.

Alloying

Through the aid of very effectve stirring, the chemical composition of the steel melt can be adjusted with high precision and consistency.
This fact has been utilized to develop a special processing route for carburizing steels with high demands on precision in hardenability.
This is discussed in more detail below.

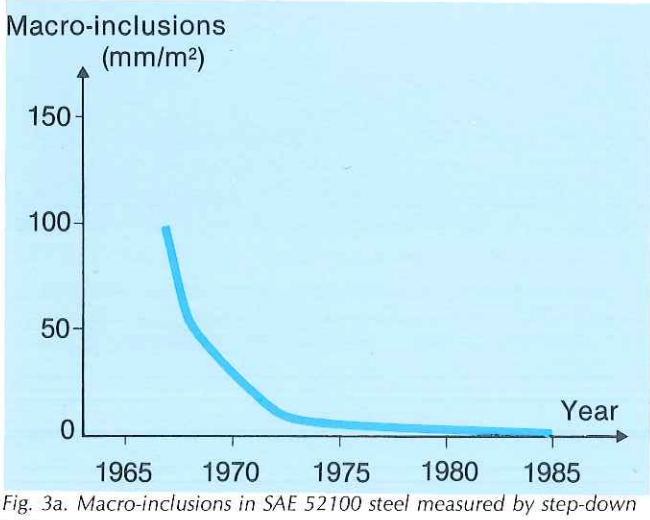

Fig. 3a. Macro-inclusions in SAE 52100 steel measured by step-down tests.

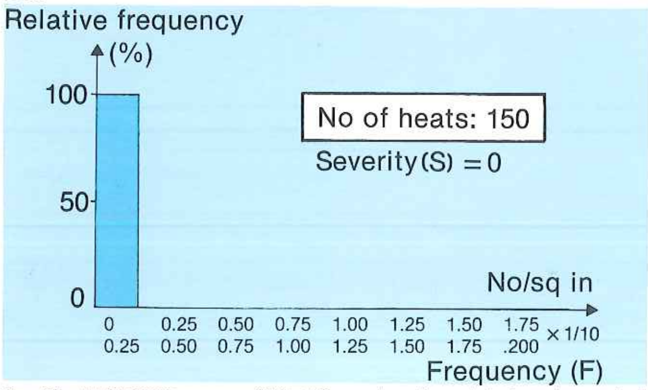

Fig. 3b. AMS 2300 tests on SKF MR produced steel during the period 1984-06 to 1985-03.

Teeming

The teeming procedure, the control of teeming temperature and the ingot design are critical factors in avoidance of large (macro) inclusions and excessive variations in steel composition (segregations) within the ingots.
SKF Steel has devoted significant development work to obtain the best teeming practice and ingot design possible.
This has resulted in a significant reduction in the content of macro-inclusions, *Fig 3,* as well as a high steel homogeneity.

Fatigue

Gears, just as rolling bearings, frequently fail from contact stress induced fatigue.
It has long been known, that the fatigue properties of steel are determined largely by the presence of non-metallic inclusions.
The influence of inclusions increases as the hardness of the steel increases (5). In *Fig 4,* where the results are based on low- and medium-carbon steels, the large variation in fatigue strength at hardness levels of 50 HR_c and above is due to variations in inclusion content.
In hard steels, as case-hardened or through-hardened high-carbon steels, the inclusion content is decisive to the fatigue strength.
Early in the research carried out into fatigue of hard steels, it was noted that different types of inclusions affected the fatigue properties differently. While hard, oxidic micro-inclusions were found to reduce fatigue life very significantly, soft inclusions such as manganese sulphides were found to have no influence at all, or even a positive effect on fatigue life.
With time, it has even become possible to differentiate oxide-type inclusions and their influence on fatigue properties.

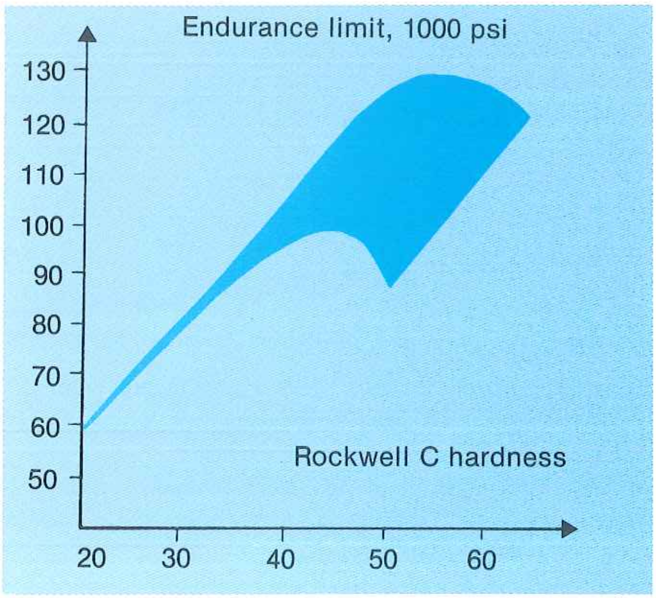

Fig. 4. Endurance limit-hardness relationship for medium carbon steels.

Oxygen content and fatigue

The influence of oxygen content on fatigue properties has been discussed in many publications. Some results worth noting are reviewed below. In (2), a summary is made of results obtained within SKF as well as published data. These data, *Fig 5,* indicate a dramatic increase in fatigue life with reduced oxygen, and thus also total oxide type inclusion content.

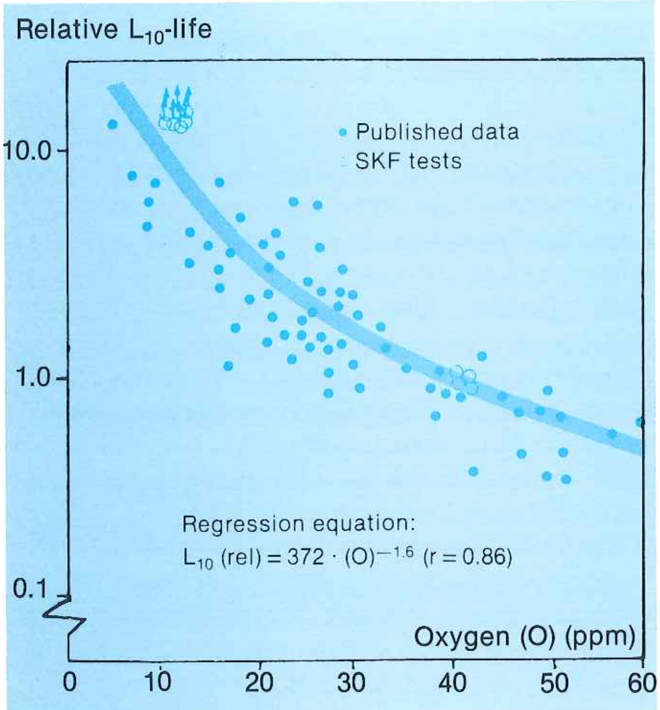

Fig. 5. Relative life versus oxygen content.

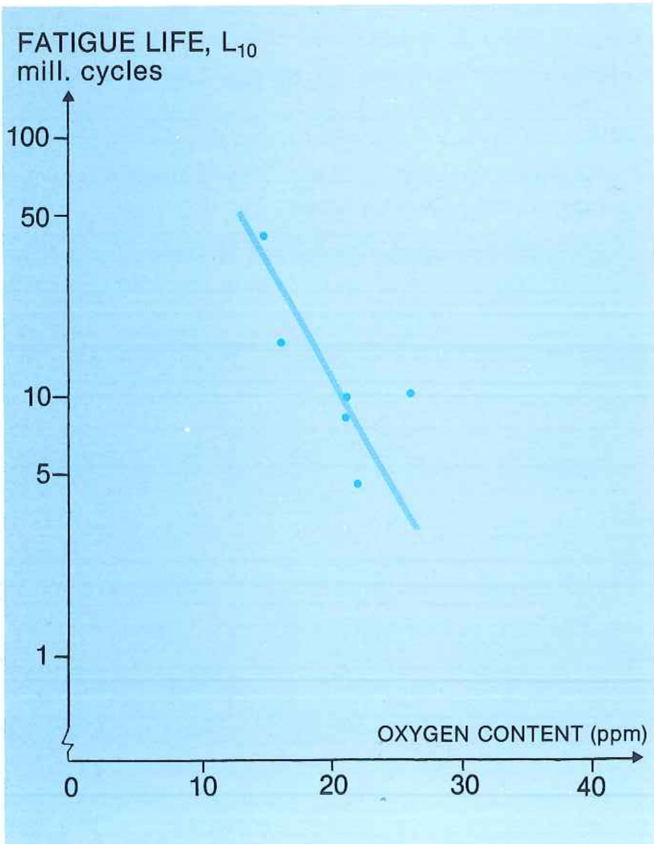

Fig. 6. Fatigue life of case hardened SAE 4320. From ref. (6).

Figures 6, 7 and *8* are produced from data presented in references (6), (7) and (8) and represent only casehardened steels.

Evidently, the oxygen content is of primary importance to the fatigue properties of case hardening steels.

In steels used for transmission components, three main types of oxidic micro-inclusions may be present

- Alumina inclusions (Al_2O_3) → B-type
- Silicates → C-type
- Calciumaluminates → D-type

B-, C- and D-type are the type classifications used by the inclusion rating standards from Jernkontoret (JK) and ASTM.

In modern, properly aluminium-deoxidized steels, the content of C-type inclusions is extremely low.

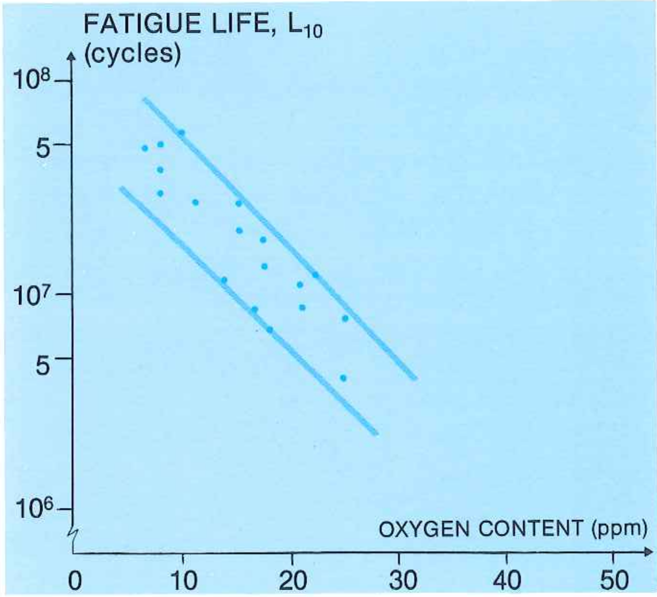

Fig. 7. Fatigue life of a case hardened steel similar to SAE 4118. From ref. (7).

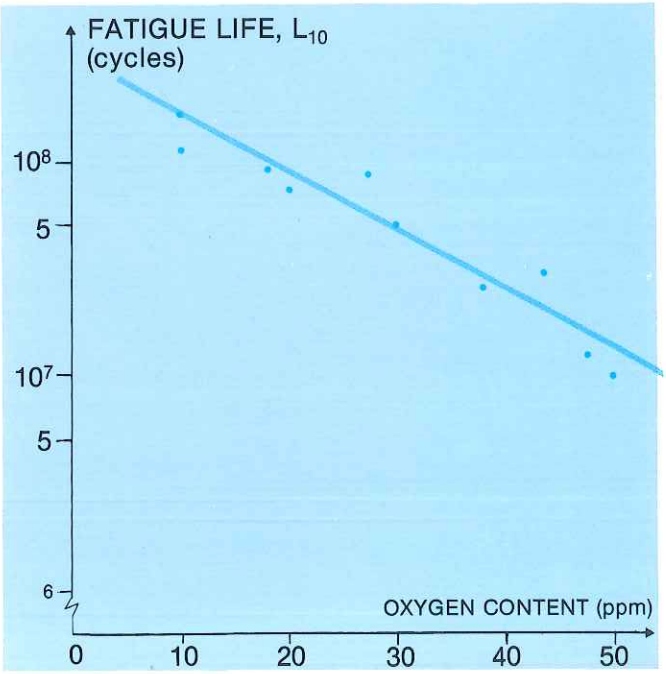

Fig. 8. Fatigue life of case hardened steels. From ref. (8).

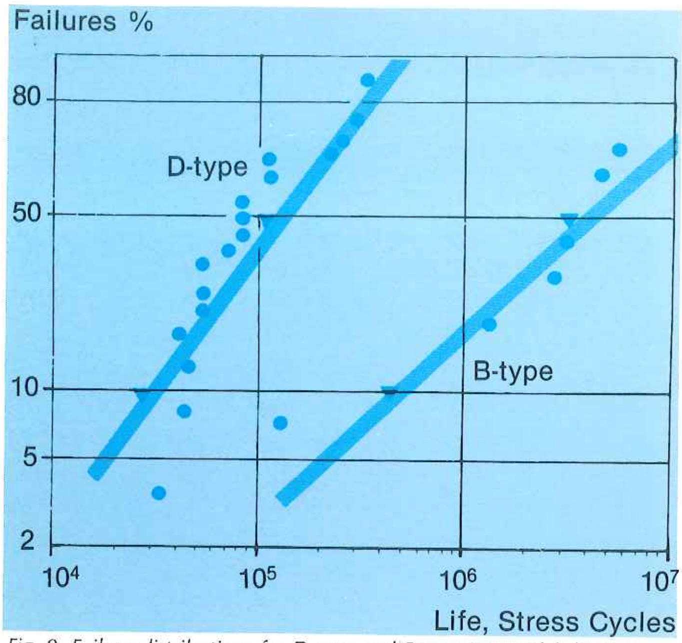

Fig. 9. Failure distributions for D-type and B-type initiated failures in rotating beam tests.

D-type inclusions are non-deformable and retain their spherical shape during rolling. They have a high concentration of CaO.

B-type inclusions are brittle, and break into stringers during deformation.

The D-type inclusions have for a long time been shown to be more harmful to fatigue properties than any other inclusion type (2, 9, 10, 11).

Fig 9 summarizes results from fatigue tests on rolling bearing steels (2). In these tests, the cause of failure in each individual rotating beam sample was examined, and the fatigue lives for samples with the same inclusion type at the initiation site were evaluated.

Sulphur content and fatigue life

Several investigations have been published where the fatigue resistance of steel with high hardness has been related to the sulphur content.
Some examples are references (12), (13) and (14).
Results from one comparative test on gear teeth strength (15) are summarized in *Fig 10.*
It seems that for gears, as well as for rolling bearings *(Fig 11),* an increase of the sulphur content even to high levels (up to about 0.10% S) will not affect fatigue resistance negatively.
For structural steels of low and moderate hardness it is well documented that sulphur is detrimental to the mechanical strength.
This is particularly true for the transverse properties of, for instance, sheet steel.
For hard steels this effect is less pronounced *(Fig 12 a),* and beneficial effects are reported in some cases *(Fig 12 b).*

Thus, an increase of the sulphur content is far less a concern in high-hardness steels (such as case-hardened or through-hardened high-carbon steels) than in structural steels.

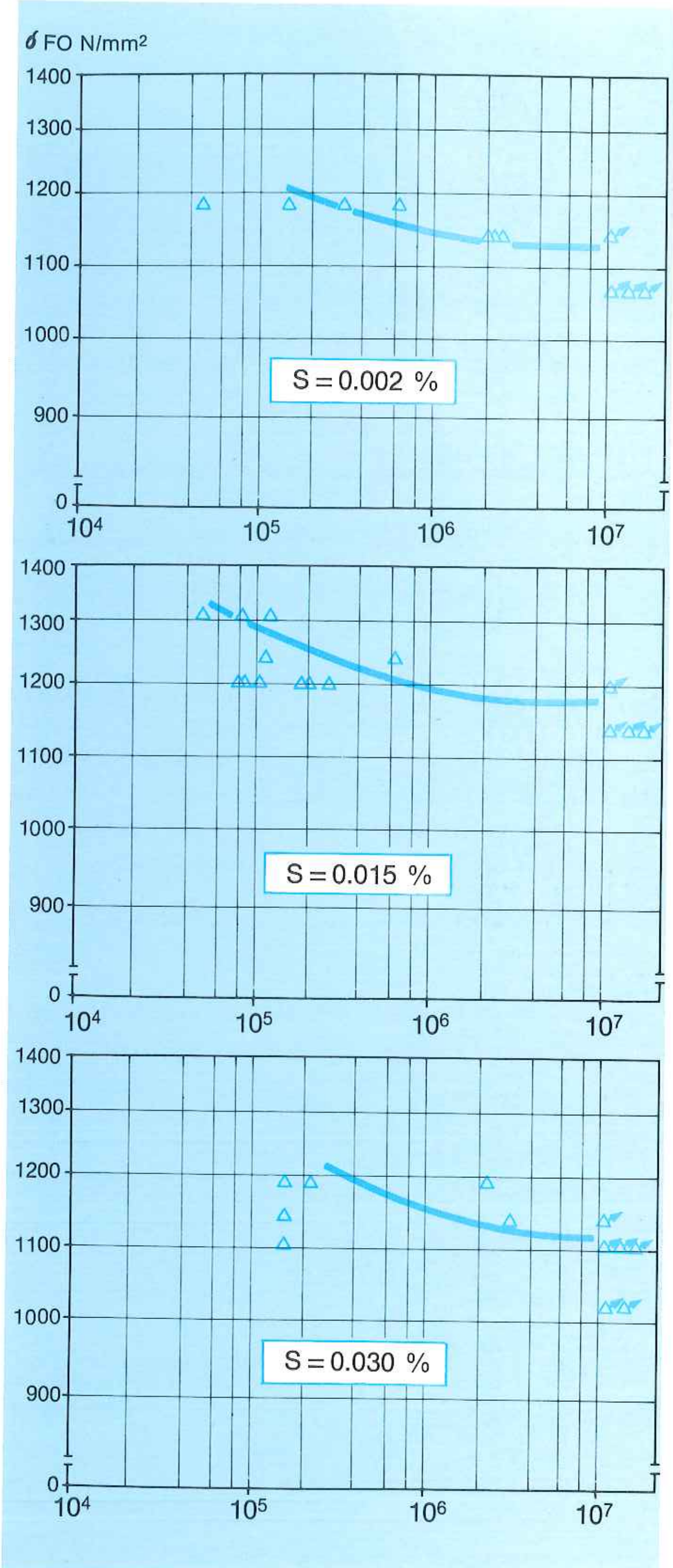

Fig. 10. Gear teeth strength in carburizing steel with varied sulphur content. From ref. (15).

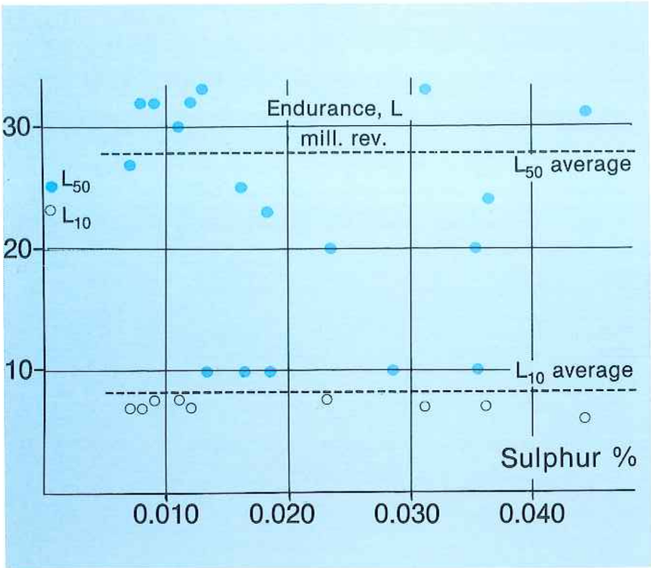

Fig. 11. Endurance values as a function of sulphur content. From ref. (12).

Free-machining steels

For the steel types commonly used for transmission applications there are three main ways commonly used to enhance machinability

- Increased sulphur content
- Lead additions
- Sulphide morphology manipulation

Increased sulphur content effects were discussed above, and large increases (up to about 0.10% S) in sulphur do not have a significant effect on the fatigue properties of high-hardness steels. *Fig 13* (a and b) compares transverse fatigue data at different sulphur levels for case hardened steel (18).

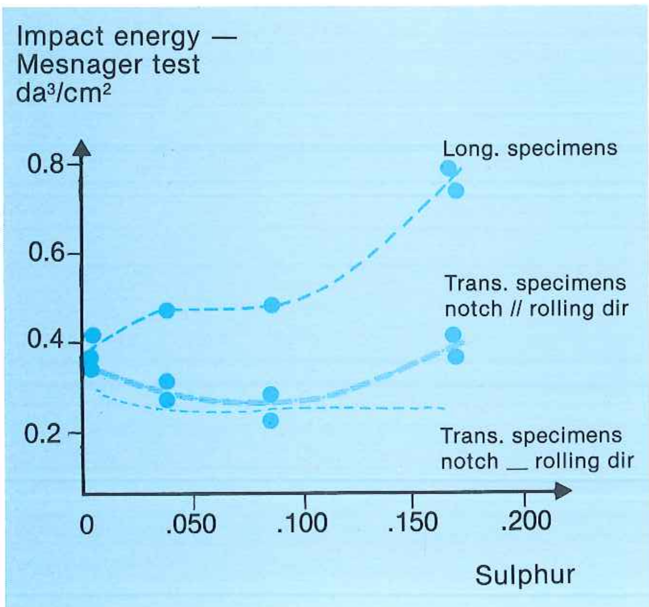

Fig. 12b. Effect of sulfur content on impact energy porperties of a hardened 52100 steel, in different directions. From ref. (14).

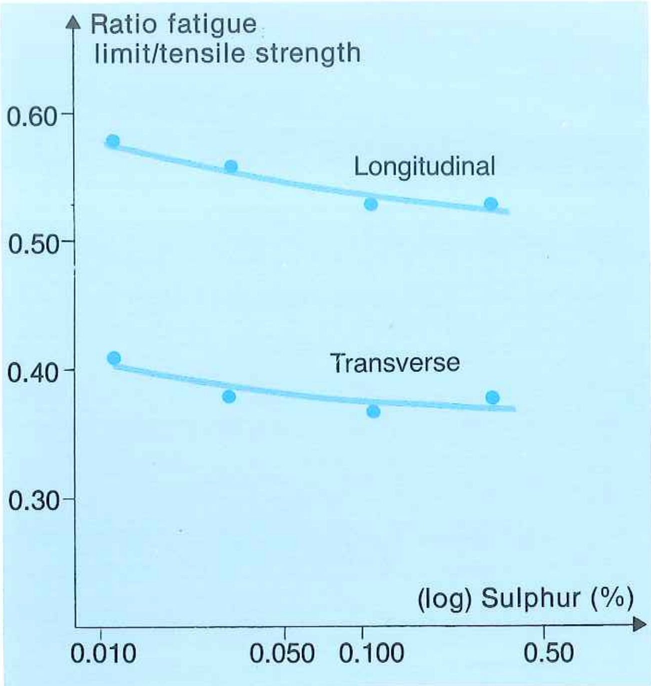

Fig. 12a. Rotating bending tests on harden and temper steel (~SAE 1040) heat treated to ~ 1000 N/mm² tensile strength. Data from ref. (22).

Lead is sometimes added to steel alone, or in combination with sulphur, to improve machinability. The lead does not affect the sulphide morphology, but forms separate sheet-like inclusions in the steel.

Lead has a marked negative influence on fatigue properties of high-hardness steels.

Fig 14 shows data presented in (7) on case-hardened steel (SAE 5120).

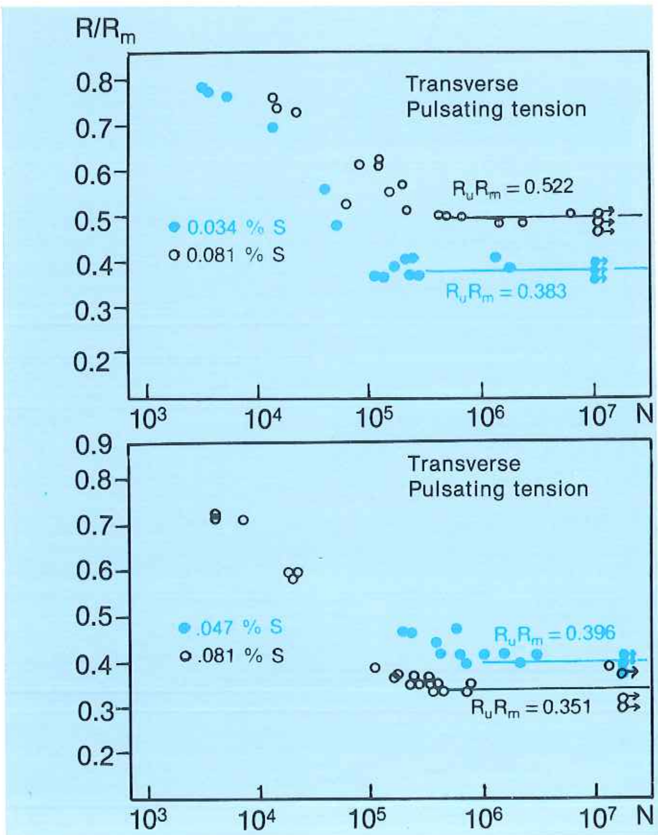

Fig. 13a. Ratio of maximum stress per cycle to ultimate strength, versus number of cycles to failure for pulsating tension. Specimens conventionally-hardened and tempered (simulates core of case-hardened component). From ref. (18).

The significant reduction in fatigue life with lead additions is also noted in rolling contact tests on case hardened SAE 4120 (16), *Fig 15*.

Sulphide morphology can be affected in several ways.

The most common practices today involve the use of injection technology (where normally a calcium compound is injected into the steel melt), or addition of an element (frequently rare earth elements or tellurium).

The effect sought is a compositional change of the nonmetallic inclusions so that maximum lubrication efficiency in the tool-workpiece contact is attained.

When sulphide morphology modification is successful the anisotropy of structural steels is largely reduced.

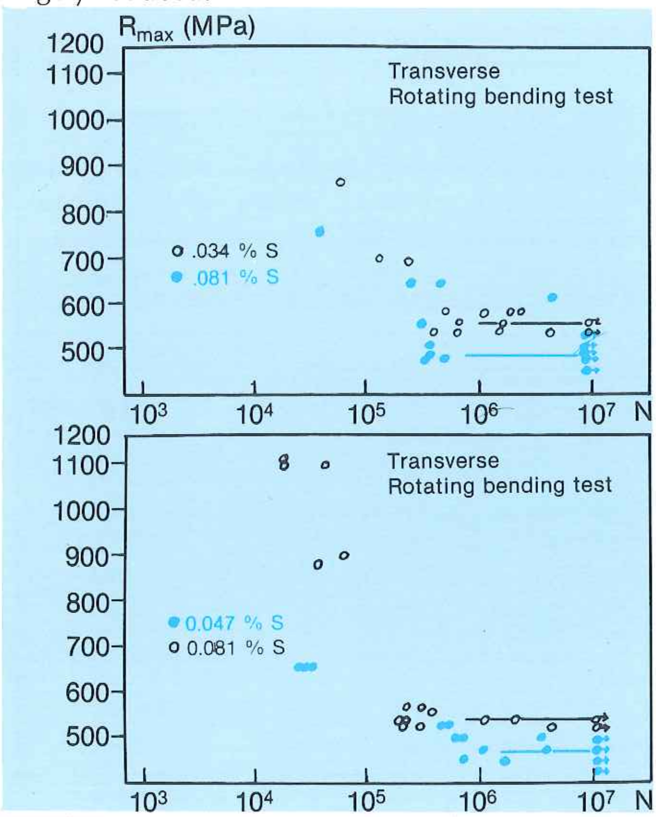

Fig. 13b. Maximum stress versus number of revolutions to specimen failure for rotating bending. Specimens in case-hardened condition. From ref. (18).

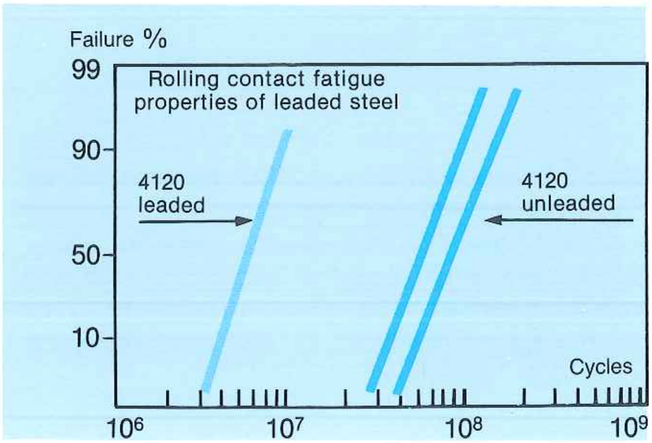

Fig. 15. Rolling Contact Fatigue Probability for Leaded and Non-Leaded AISI 4120 Type Steel. From ref. (16).

The effects on high-hardness steels are less well documented, however.

Fig 16 recapitulates some fatigue tests performed at SKF Steel (17).

In these tests, longitudinal samples of case-hardening and harden-and-temper steels were heat-treated to different hardness levels.

For each steel type, conventional and SiCa-injected variants were tested.

Evidently, hardness levels above about 50 HR_c give reduced fatigue strength.

This result is an effect of the generation of calciumaluminate oxide inclusion by the injection of SiCa.

For high-hardness steels, the control of oxide-type, and in particular calcium-rich non-deformable (D-type), inclusions is imperative to attain high fatigue resistance.

The content, and the shape, of sulphide inclusions only has a marginal effect on the fatigue properties of high-hardness steels.

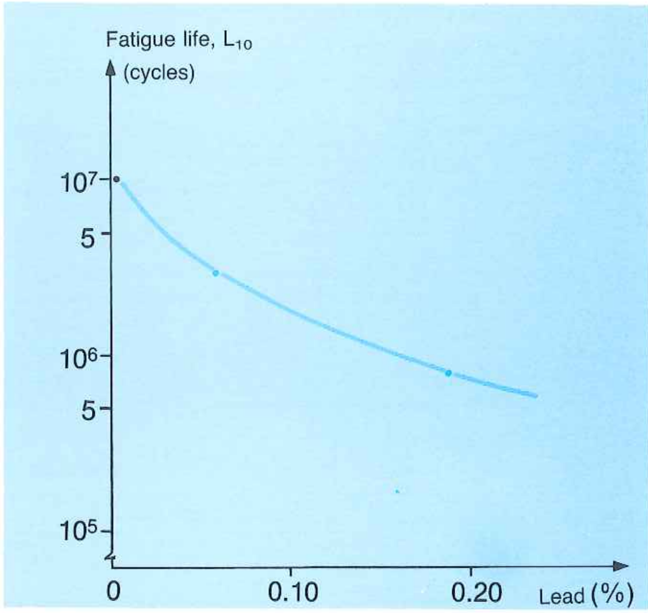

Fig. 14. Fatigue life of case hardened ~SAE 5120 with lead additions. Data from ref. (7).

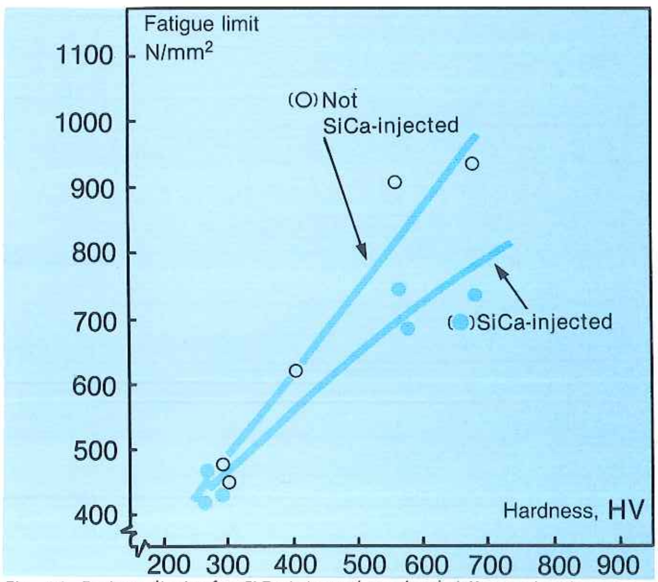

Fig. 16. Fatigue limits for SiCa-injected steels at different hardness levels. From ref. (17).

Transmission Steel Specifications

The need to limit the amount of non-metallic inclusions has long been recognized by transmission component producers as rolling bearing manufacturers.
"Bearing quality" is a term frequently used to specify steel for critical components.
SKF Steel has designed three different quality levels to meet the growing demands on cleanliness in quality critical applications.
These specifications are the in-house limits of oxygen content and inclusion contents to which **all** SKF MR steel products are manufactured.
Cleanliness specifications for SKF MR steel are based on inclusion ratings procedures as defined by the ASTM A295 specification.

Industries standard

The cleanliness standards used by the automotive and rolling bearing industries today are ASTM A534, ASTM A295 and ASTM A535.

ASTM A534 is used mainly for carburizing steels, and gives rating limits for micro-inclusions as follows.

A	B	C	D
Th He	Th He	Th He	Th He
3.0 2.0	3.0 2.5	2.5 1.5	2.0 1.5

ASTM A295 is used for through-hardening high-carbon steels (SAE 52100 type):

A	B	C	D
Th He	Th He	Th He	Th He
2.5 1.5	2.0 1.5	2.0 1.5	1.5 1.5

ASTM A535 is used for carburizing and SAE 52100-type steels where high demands are made on cleanliness (this specification is often used for remelted-ESR/VAR-steels):

A	B	C	D
Th He	Th He	Th He	Th He
1.5 1	1.5 1	1.5 1	1.5 1

It should be noted that the A535 specification has an additional requirement on the maximum number of fields allowable.

SKF Steel specifications

SKF Steel has devised three different cleanliness specifications for the total production program. These specifications are not related to steel grades, but instead specify quality levels.
The three variants are
SKF MR Quality. This is the basic quality level for all steel produced at SKF Steel. Unless otherwise specified, this quality level applies to all steel produced.
SKF MR Bearing Quality. This quality level is mainly used for products with high demands on consistency and fatigue resistance. All SAE 52100-type steel and all alloyed valve-spring steels are produced to this quality as standard.
SKF MR Premium Bearing Quality. This quality level is used for steel grade variants directly intended to replace remelted (ESR/VAR) steel.
The details of the specifications are given in SKF Steel cleanliness specifications.

A comparison of the SKF Steel specifications show that the inclusion rating numbers are heavily reduced compared to the commonly applied inclusion rating standards.
In particular, the D-type and C-type inclusions have been severely restricted in order to ascertain high fatigue strength.
The ASTM A534 and A295 specifications do not contain limits for macro-inclusions.
This is a factor of prime importance to product reliability as macro-inclusions are almost immediate fatigue initiators.
The ASTM specifications are therefore often complemented with the AMS 2301 ("aircraft quality") and AMS 2300 ("remelt quality") specifications.
All SKF MR cleanliness specifications fulfill AMS 2300 specifications.

Statistical process control

In order to assure that the requirements of the specifications are fulfilled, and that the steel quality is continuously improved, SKF Steel has introduced statistical process control (SPC) procedures for oxygen, titanium and micro-inclusions.
SPC, which is a general tool for effective process development, is presently under introduction at SKF Steel in a number of areas.
Figures 17 and 18 show control charts for SAE 52100 steel used to control and improve oxygen and B-type (thin) inclusions. Corresponding charts are maintained for titanium, and other inclusion types than B-type, thin.
The charts of figures 17 and 18 give the range and average of consecutive heats of SAE 52100 produced in Hofors in the early spring of 1985.

Comparison of these values to the SKF Steel cleanliness specifications show the capability and precision of SKF MR steel.

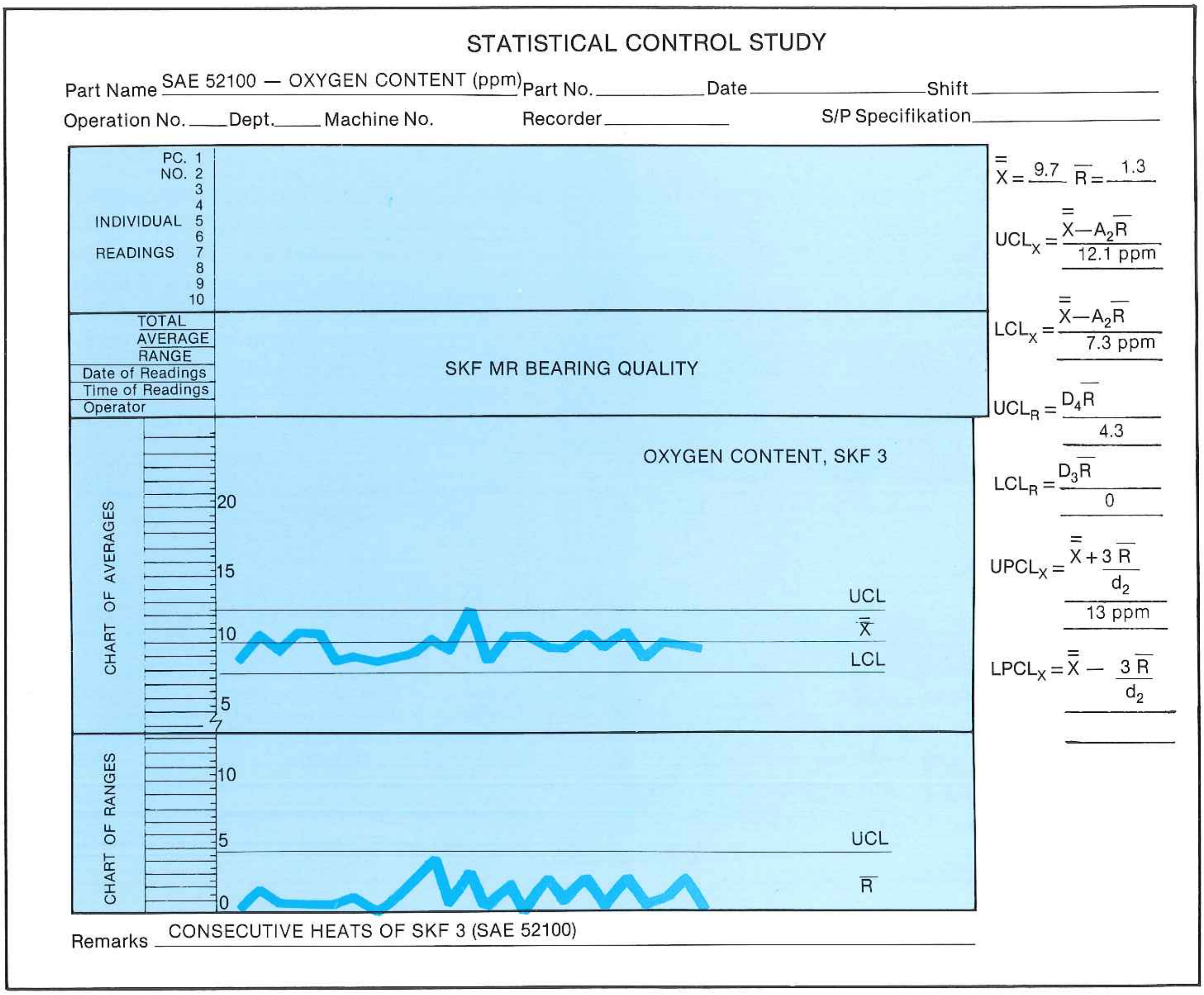

Fig. 17.

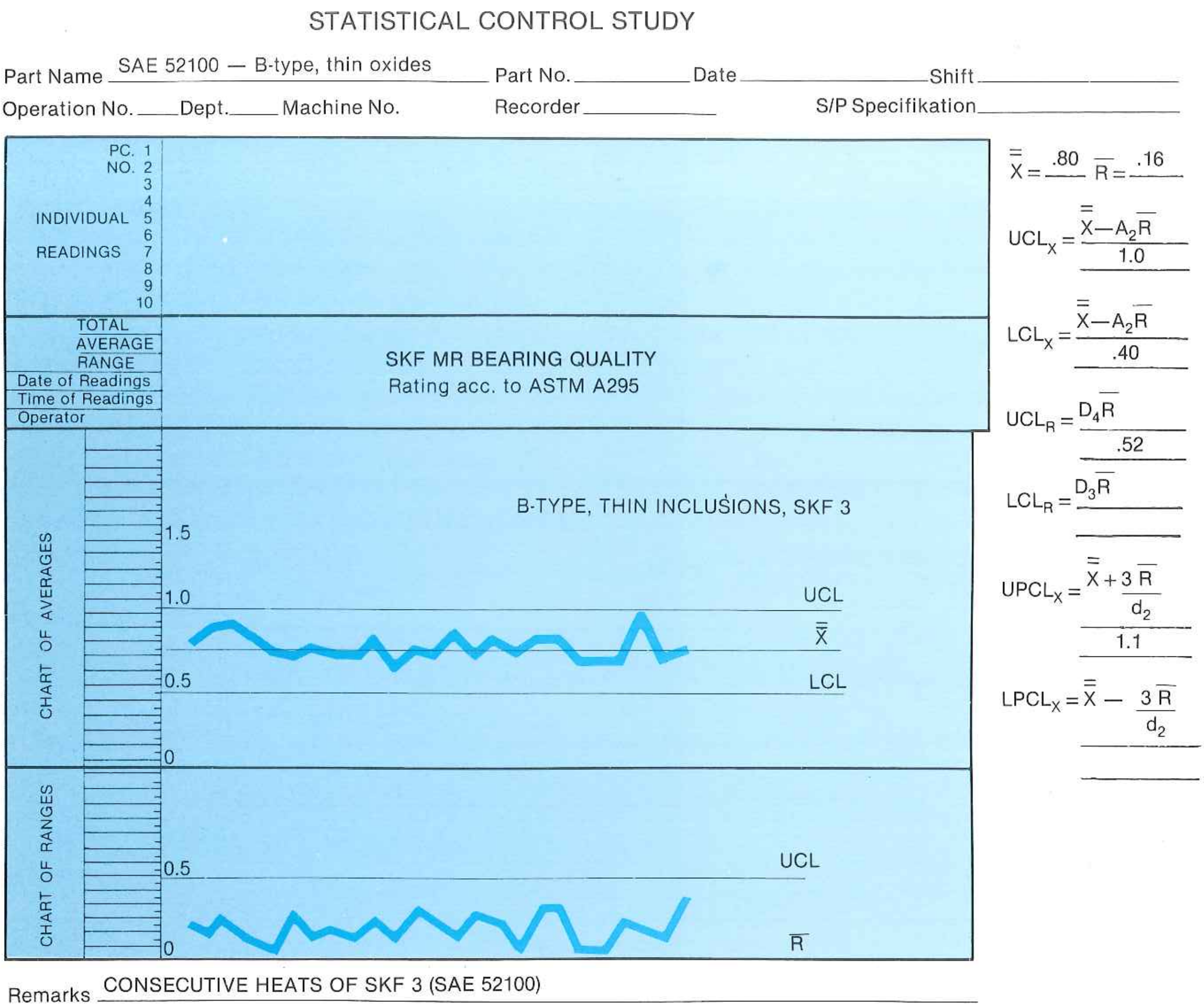

Fig. 18.

Machinability

General

The concept "machinability" is very often found in the literature and in everyday use without it being clearly defined. In order to enable people to discuss machinability in depth, one must establish parameters that — one way or the other — can be measured and followed up.

Apart from the problems we face already when trying to define machinability, we must not forget its complexity. How easy or difficult it will be to produce a specific component depends on a variety of parameters, such as:

— type of machining
— the machine used and its condition
— the tools used and their condition
— the shape of the component
— the quality of the coolant supply
— the quality of the workpiece material

This indicates why it is so difficult to define machinability from a general point of view, different machining criteria will have to be used for different machining situations.

Machining criteria

Figure 19 shows the machining criteria normally considered (19).

The significance of such criteria varies according to different conditions and different applications. Tool wear is probably still the most important criterion, due to the cost of current inserts, and the need for them to last as long as possible at as high a cutting speed as possible.

In the near future, chip formation will be just as important as tool life, due to developments in production with limited manpower, PLM, where one operator handles a group of machines or even where the third shift is fully automated. As a result of this, the machines can not be supervised throughout production, which is why controlled chip formation to prevent formation of "birds nests" will be of the utmost importance.

The cutting forces should be kept as low as possible to avoid overloading of the insert, reducing the risk of chatter and reducing the power required for the machining.

On finishing cuts, the surface finish is essential and often decisive in when to index the insert, which affects the total production economy.

Development and trends

The simple fact that nearly 80,000 tons of swarf is produced within the SKF group indicates the importance of machinability to the industry of today. Over the years, metal removal rates have increased steadily. *Figure 20* shows the time in cut to rough turn a low alloy steel shaft of 4'' (100 mm) diameter and a length of 20'' (500 mm) (19).

As can be seen, the cutting time today is less than 1 minute compared to well over 100 minutes at the beginning of this century. There are three main reasons for this:

— developments in machinery
— developments in tools
— developments in workpiece material

Close to 50% of the new investments in machinery are NC or CNC equipped, combining high efficiency with the availability of high revs and in-line automtic control of parameters such as tool wear, workpieces, tolerances etc.

We can distinguish between three major lines in tool development. Clamping systems, cutting geometries and tool materials. The clamping systems have undergone a dramatic change from brazed tips to indexable inserts which are kept in the seatpocket by means of a top clamp or even a centre lever or screw, allowing indexing within 10 seconds only.

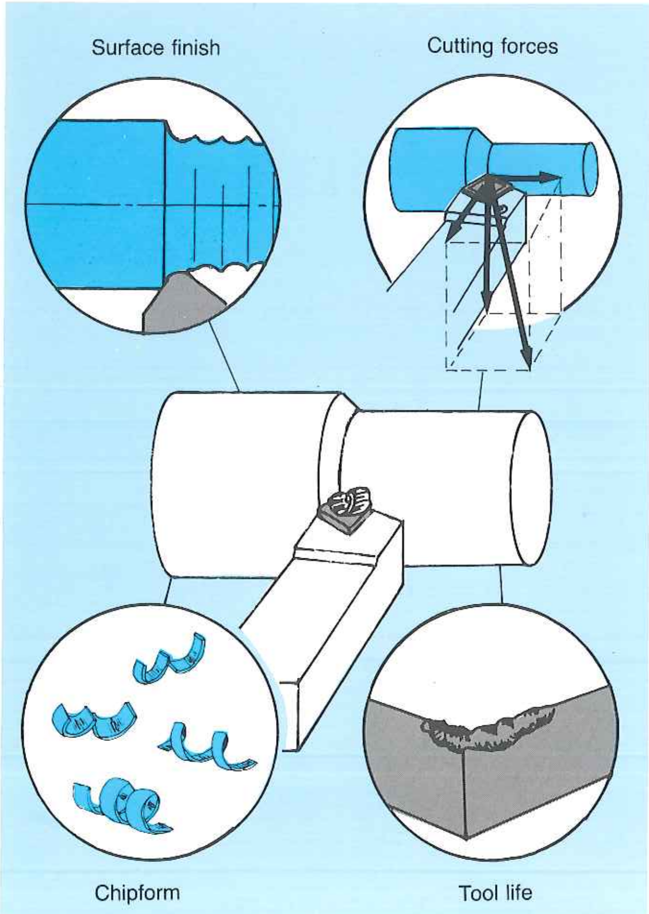

Fig. 19. Main machining criteria.

At the same time cutting geometries have progessed from flat, negative inserts to double-sided or positive inserts with pressed-in chipbreakers, giving the user the choice of a geometry suitable for the job. The most significant progress, however, has been the development of tool material from tool steel through HSS to the present-day double-and triplecoated cemented carbides. The coating technique offers a combination between a cemented carbide substrate and a coating that is specially adapted to the type of operation.

As a result of this we have reached cutting speeds well in excess of 300 m/min, which is approximately 3 times faster than 15 years ago, *(see figure 21).*

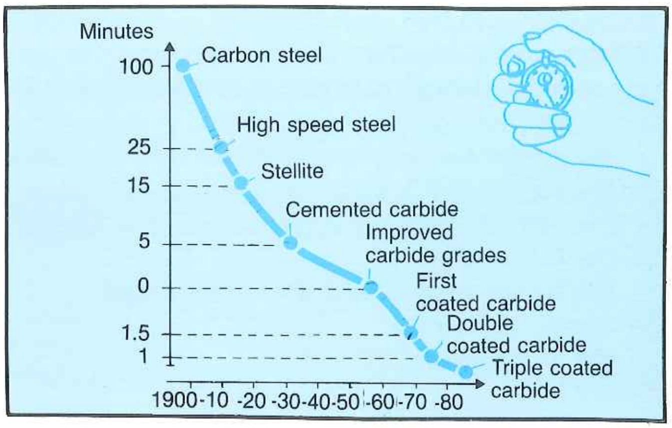

Fig. 20. Development of time in cut versus tool material.

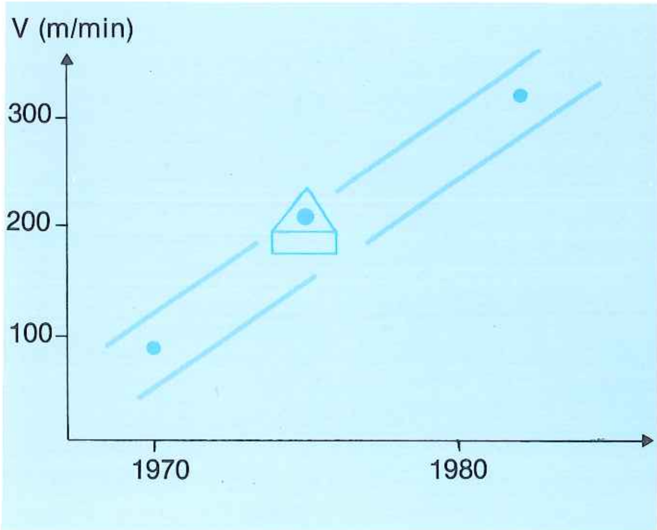

Fig. 21. Development of the cutting speed over the last 15 years.

One relevant question is "What will happen over the next decade"? There is naturally no definite answer, but a few trends are obvious. As already meantioned, there is a major trend towards PLM, which requires reliability rather than the highest cutting speed. Due to increased demands on flexibility, customer oriented production, shorter lead times and smaller (shorter) series (batches), drafting will have to rely more heavily on CAD/CAM. The unmanned remote-control production cell is here to stay. The machines will be furnished with feed-force monitoring, in-line gauging of the components, measuring probes for tool wear, robots and magazines for automatic change of tools and workpieces etc. All factors indicate the importance of a proper chipform and a predictable tool life, which both require workpiece material with excellent and, especially, repeatable "machinability".

Now, how can the "machinability" of the workpiece material be affected? The answer is "in many ways through different parameters" such as:

- the analysis
- the structure
- the hardness
- the surface finish
- the tolerances
- the straightness of bars and hollow bars (screw machines)
- the cleanliness
- additives
- stresses
- cold working

How these parameters affect the machinability is described in detail in reference (20), which is why we shall concentrate on cleanliness and additives in this report.

Effects of cleanliness and additions on machinability

Non-metallic inclusions are always present in steel. The amount, the type, the size and the distribution of the inclusions vary according to the melting process. The inclusions are known to affect the machinability in a positive or negtive way. Four major parameters have been listed by Kiessling (21) where the criteria for a "positive" inclusion are listed accordingly;

1) The inclusions should act as a stress raiser in the shear plane of the swarf (chip) so initiating crack formation and embrittling the chips. The chip-tool contact length then decreases which is of advantage. The inclusions should not however, be such strong stress raisers that the workpiece cracks.

2) The inclusions should participate in the flow of metal in the flowzone, increasing the shear of the metal, but should not cut through the plastic flow of metal thus damaging the tool surface.

3) The inclusions should form a diffusion barrier on the rake face of the tool at the temperature of the tool-chip interface. This temperature depends on several variables, especially the cutting speed.

4) The inclusions should give a smooth workpiece surface and not act as abrasives on the flank face of the tool.

By tradition, additives like sulphur, lead, bismuth, tellurium and selenium have been considered when discussing supreme machinability, or if preferred, "free-cutting" steels. We have now reached a stage at which steels are launched with "free cutting properties" using calcium and controlled sulphur contents instead of lead, tellurium etc. The calcium treated (or calcium-injected, as at SKF Steel) steels are found to offer increased cutting speed and lower cutting forces, but like other additives, calcium forms non-metallic inclusions in the steel. Calcium is not the saviour people expected it to be, (see the chapter on fatigue), but used in the proper way, calcium-injected steels will reduce machining costs compared with non-added steels.

In *figure 22,* a list of "positive and negative" inclusions are given.

By positive/negative we mean the total effect on the machining operation, i.e. chipformation, toolwear, surface finish etc.

+	−
MnS (A-type)	Macro inclusions
Mn (S, Se)	Al_2O_3 (B-type)
Mn (S, Te)	SiO_2 (C-type)
Pb	Ti
Bi	
Ca-silica aluminates	

Fig. 22. Additives and inclusiontypes detrimental or beneficial to the machinability.

Negative inclusions

Macroinclusions are normally very hard and brittle, thus causing rapid tool wear or catastrophic tool failure. For this reason, macroinclusions are not desirable in steels. The development work within SKF Steel and the improvement of our steelmaking process has led to a very low level of macroinclusion, *figure 3.*

The oxidic microinclusions (B and C-types) are also hard, brittle and abrasive, causing abrasive tool wear. The number of oxidic microinclusions is directly related to the oxygen contents, which is why the effect on machinability versus oxygen contents is a way of presenting the influence of oxidic microinclusions, *figure 23 and 24 (8)*.

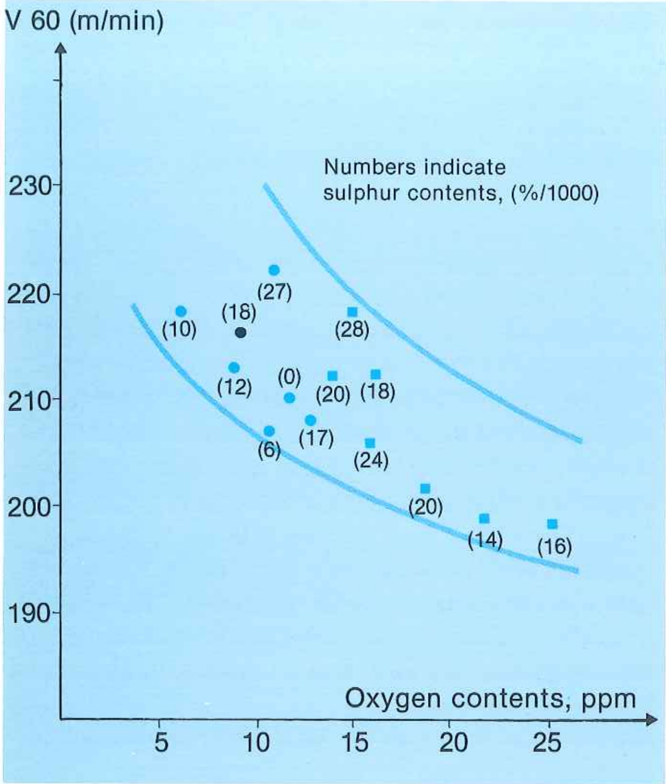

Figure 23 HSS tool life on SAE 8620. Versus oxygen contents. From ref (8).

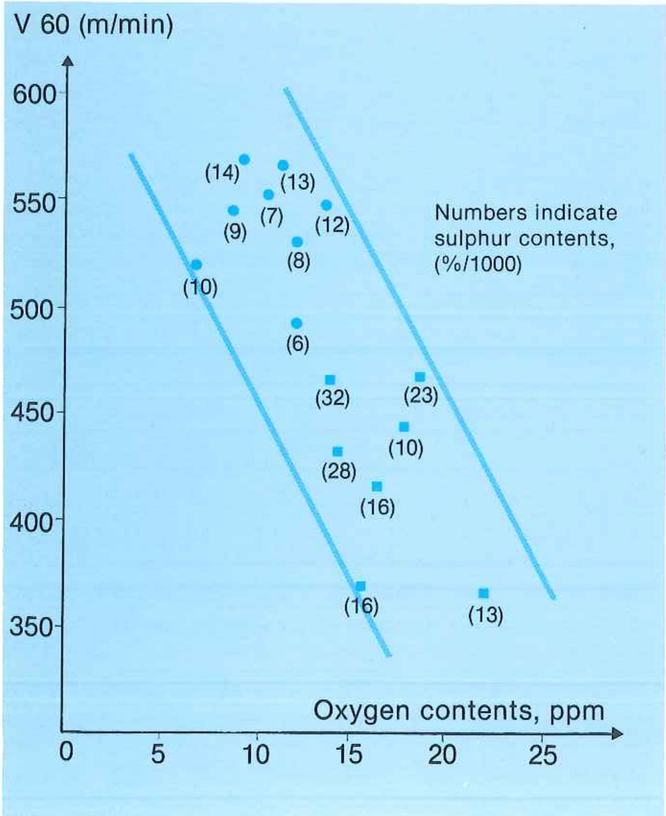

Figure 24 Carbide tool life on SAE 8620. Versus oxygen contents. From ref (8).

The SKF MR process enables production of steels with very low oxygen contents.
Titanium forms titanium nitrides carbonitrides, which also are hard and abrasive, which is why they affect machinability in much the same way as B- and C-type inclusions.

Beneficial inclusions

Sulphur has been the most popular additive throughout the years. If sulphur is added to steels containing manganese, manganese sulphides are formed. Sulphides affect the chipformation as well as the tool wear. The manganese sulphides seem to reduce the shear stress in the primary deformation zone and even to provide fracture initiation spots by establishing layers with lower shear stress in the secondary deformation zone, thus affecting chip breaking (22).
An additional effect that reduces tool wear is the formation of friction-reducing lubricating layers at the tool-chip interface and possibly even a diffusion barrier preventing the diffusion of tungsten, cobalt and iron between the chip and the tool.

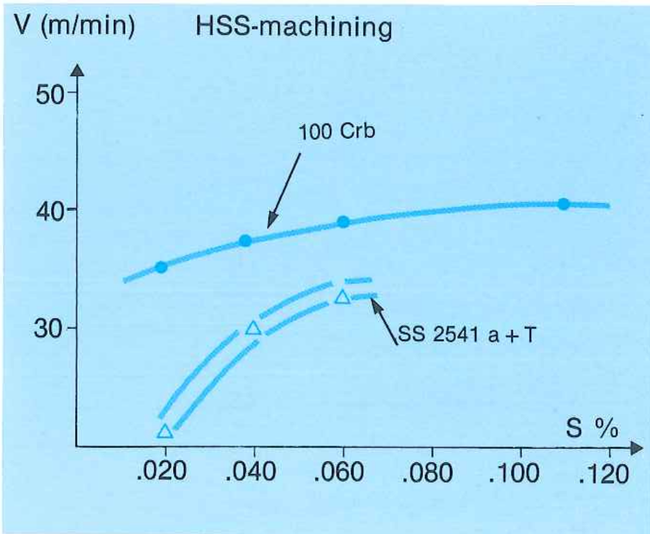

Figure 25. Cutting speed as a function of the sulphur content (3), (23).

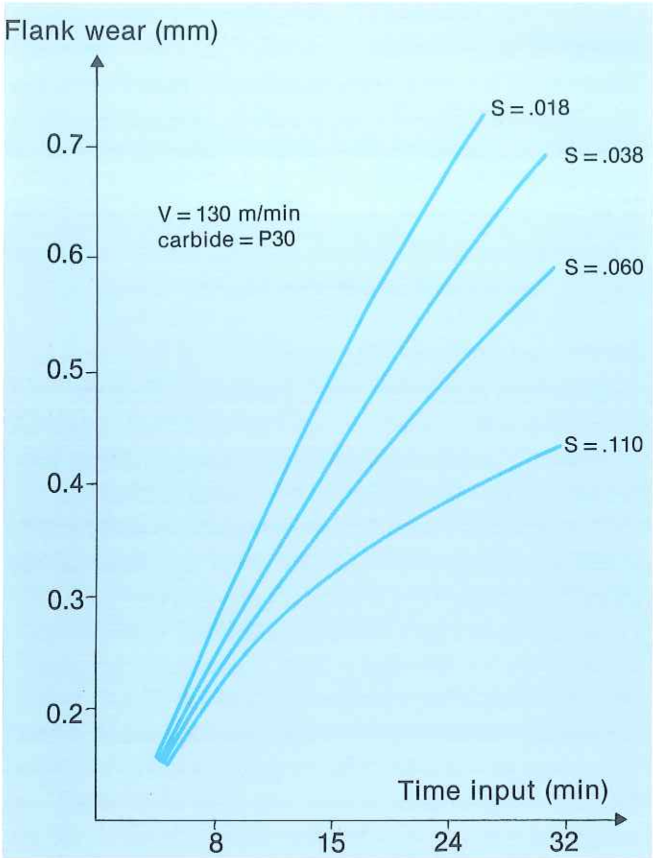

Figure 26. Influence of sulphur content on flank wear (23).

Reducing a tendency to welding (BUE), sulphide inclusions have been found most effective in the low-speed range, i.e. HSS machining applications with V < 80 m/min. (24).

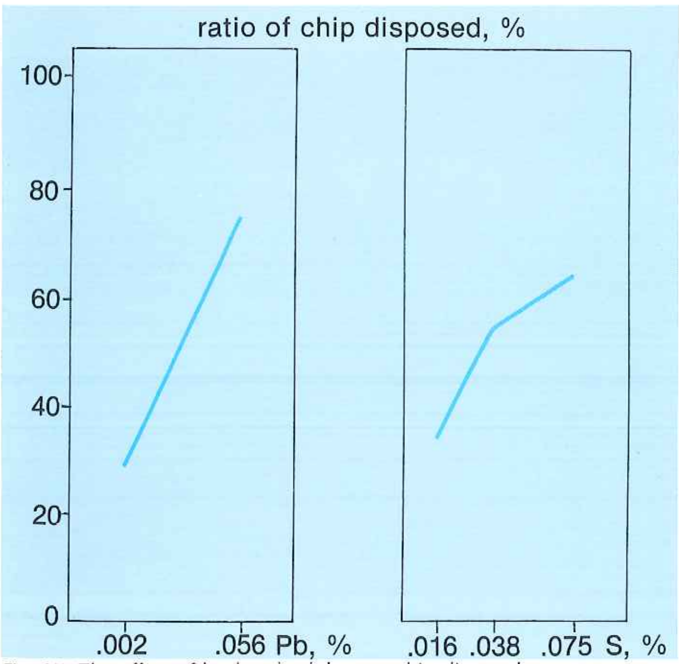

Fig. 27. The effect of lead and sulphur on chip disposed.

Discussion about the effect of selenides and tellurides has been animated. References can be found that express a full range of opinions from no effect or even a negative effect to a positive effect on chip formation, surface finish and productivity (+10 to 30%) (25).

SKF Steel has performed its own tests on steels to which tellurium has been added without finding a significant improvement over untreated or leaded steels, *Figure 28.*

The situation is pretty much the same for Bismuth. Although similar to lead (and used in combination with lead) some literature presents negative results compared with untreated or leaded steels (26).

Lead is the second most popular additive and has been widely used over the last thirty years. Its use is likely to decline however, as there already are restrictions in the manufacturing of leaded steels due to lead's toxity. Lead is said to act as an internal lubricant affecting the friction and the shear stress (just like the sulphides) thus reducing the chip-tool contact length, reducing the cutting forces and lowering the cutting temperture, thereby decreasing tool wear and improving the chip formation (shorter, curled chips).

The solubility of lead in iron is close to zero, which is why metallic lead is found in the steel, often in combination with sulphides ("lead-tails"). There is a distinct effect on chip formation (27) (in this reference defined as chip disposal), already at low contents, *figure 27;*

This is found to coincide with SKF Steels own findings. Tests run do not show any other

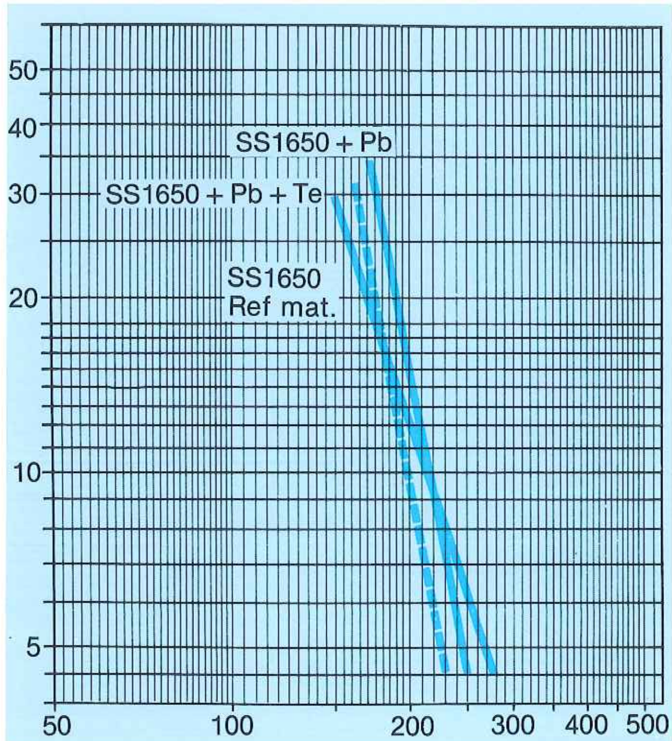

Fig. 28. Cutting speed versus tool life for different steeltypes, SS 1650, SS 1650+Pb, SS 1650+Pb/Te.

advantage from the addition of lead over SKF MR produced steel, *see figure 28.*

Paying attention to a somewhat lower sulphur content in the reference heat, the three variants fall within the same machinability range.

SKF Steel has also performed a single-point HSS-

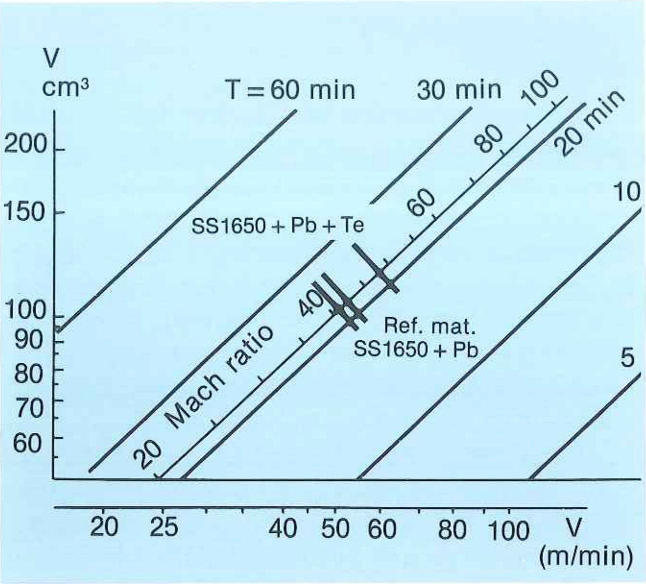

Fig. 29. Single-point HSS milling test.

steel miling test on the same steels, getting comparative results, *figure 29.*

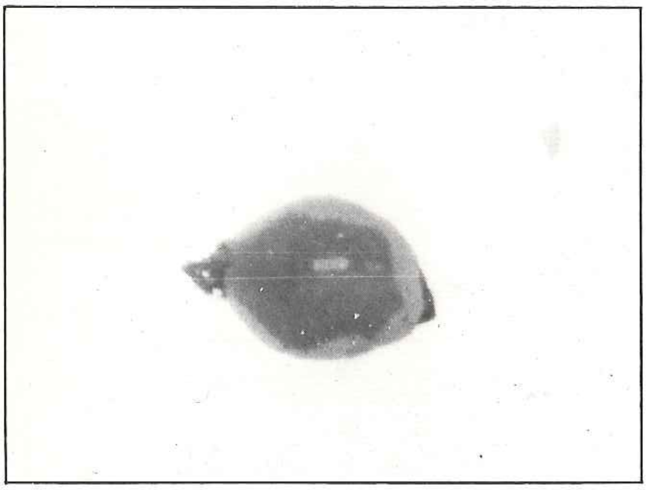

Fig. 30. Inclusion in calcium injected MR steel.

The lead tellurium steel shows an improvement over the others in the HSS test. Even considering other metallurgical and mechanical factors such as yield point and analysis, Pb/Te has a positive effect, although less than 15%.

Ca-treated steels

We have deliberately not discussed the effect from calcium yet, but we will. There is a lot to be found in the literature on calcium-addition, inclusion morphology and the effect on machinability (3, 24, 25, 26, 28). All these reports are more or less positive to calcium and its improvement of tool wear.

The main criterion is probably that calcium — when controlled — forms complex globular calcium-oxides which are beneficial for machining. These oxides are softer and less abrasive to the tool compared to other oxides. They also melt at rather low temperatures, 750°C, above which they act as a lubricant and a diffusion barrier just like the sulphides. *Figure 30.*

Since such edge temperatures are present mainly when carbide machining, optimum effect was anticipated at high cutting speeds, which SKF Steel also found, *figure 31.*

In the single-point milling test with HSS, the calcium-added steel performs as well as the lead + tellurium steel, resulting in a machining ratio of 47. These results are extremely good. SKF Steel has found a calcium-injected SKF MR-steel to have as an average 25% better machinability regarding cutting speed. (29).

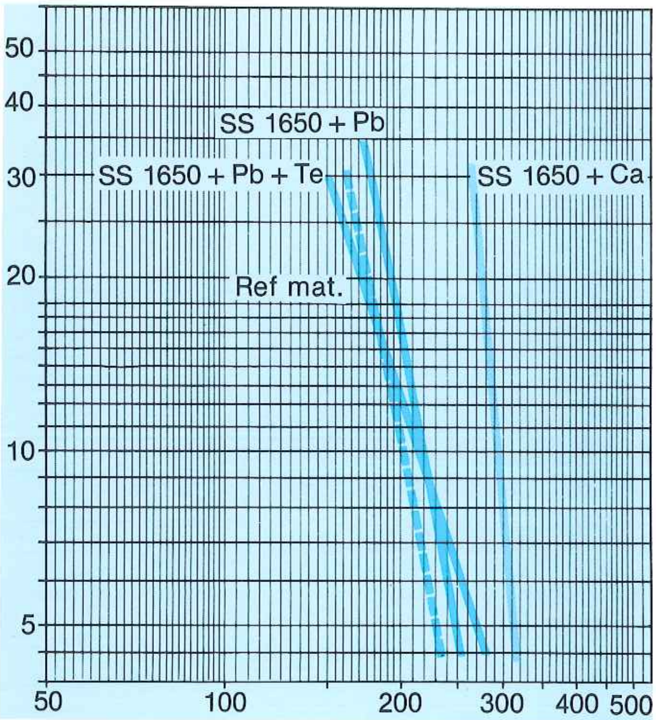

Fig. 31. vT diagrams for carbide machining.

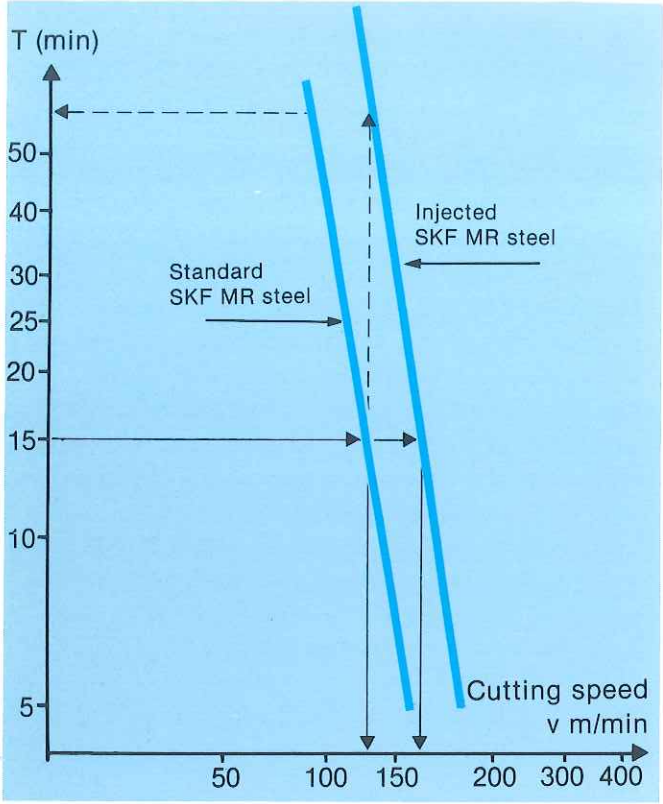

Fig. 32. vT diagram for Ca-treated and untreated SS 2541, Q+7.

The other way to utilize the positive effect (which also falls in line with the development towards security), is to follow the dotted line in figure 31, where one finds that tool life increases by another 100—200%, if the original cutting speed is retained.

In most cases, a steel with a very low macro-inclusion content, with an addition of calcium and a controlled sulphur content, will definitely be a factor to count on in future.

Hardenability

Hardenability is most easily described as the hardness that a steel attains after austenitization and quenching.

There are several ways available to measure hardenability, but by far the most common is the end-quench (or Jominy) test.

In the end-quench test, a test bar is austenitized at a defined temperature and water quenched at one end.

The hardness is measured along the test bar, and the result of the end-quench test is a graph of hardness versus the distance from the quenched end, *Fig 33.*

End-quench testing is a drastic simplification of the actual hardening process, in particular in comparison to case-hardening.

Case-hardening is a complex process which requires control of a large number of parameters such as case carbon content, carburizing depth, grain size, and after quenching, surface hardness, hardness profile and core hardness.

One factor of major interest to transmission component producers is the distortion caused by case-hardening as this determines turning and grinding allowances, and thus manufacturing cost.

To meet current requirements on distortion control and control of core properties, SKF Steel has devised the **extra-hardenability controlled carburizing steels.**

It has long been known that the chemical composition of the steel largely determines the core hardenability of carburizing steels.

Several models have been developed to predict hardenability of carburizing steels from chemical

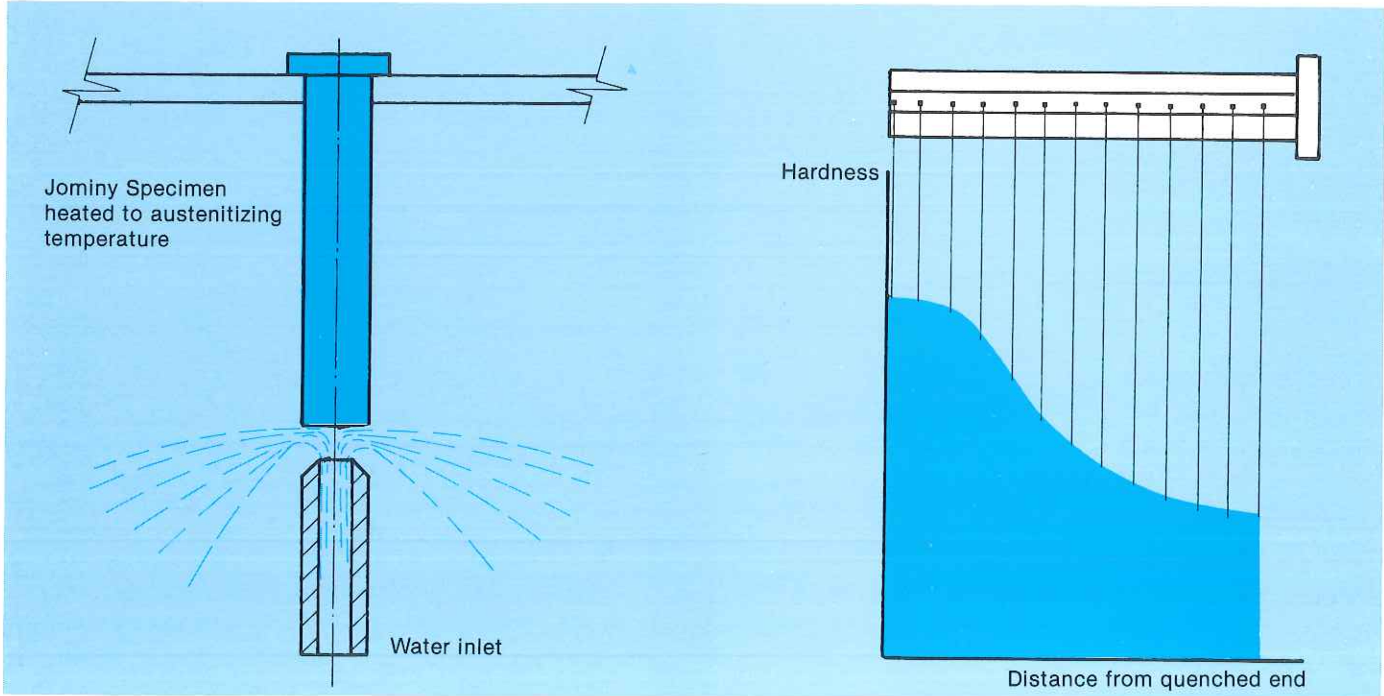

Fig. 33. Jominy testing.

composition. Some of these have been developed into slide-rule calculators, other models have been based on regression analysis (30).
The regression formulae developed in synthetic steels, or from published data or end-quench bands, always lack precision due to what is often called the "mill-factor". This factor derives from the fact that different steelmakers have different deoxidation technology and different raw material supplies.
SKF Steel has developed a regression model based on a very large number of heats produced at SKF Steel.
Based on the measured end-quench curves, seprate regressions were derived for twelve separate end-quench distances, and the prediction power of the model has been shown to be very high (31).
In fact, the deviations obtained between predicted and measured hardenability are smaller than the scatter of the end-quench test, *Fig 34*.

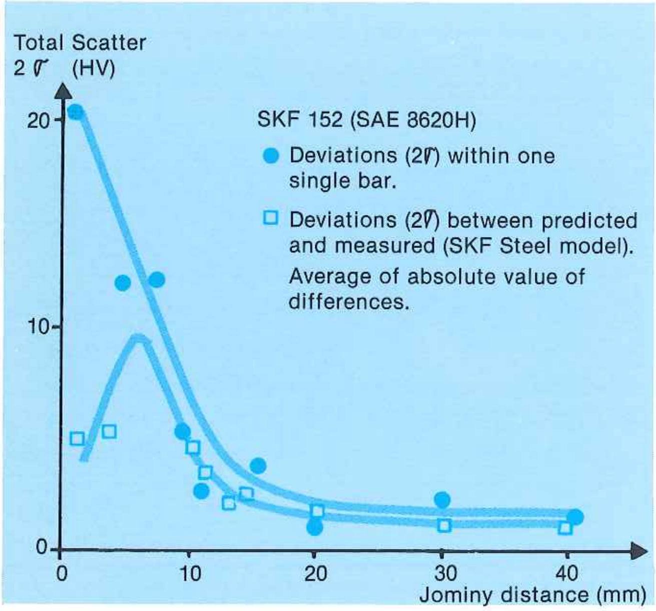

Fig. 34. Deviations within one single bar, and between measured and predicted end-quench data. From ref. (20).

However, the aim of this model development was not to derive a prediction tool which was better than the ones already available. The objective was to find a way to **produce** carburizing steel to a desired hardenability with high precision.
This has been made possible by "reversing" the end-quench calculation, so that a given hardenability demand is used to produce a certain steel composition.
In practice this works a follows.

1. A customer desires a certain end-quench curve for the steel grade SAE 8620H.
2. Conventionally, the customer will get a heat which is certified to be somewhere within the H-band of SAE 8620H, *Fig 35*.
3. In the SKF Steel system, the customer is allowed to pin-point any three points on the end-quench curve that is desired, *Fig 36.*
4. In giving this requirement to SKF Steel a first off-line check is made at the mill by SKF Steel's technical customer services:
   — Do the points fall inside the min/max limits for SAE 8620H?
   — Do the three points fall on an end-quench curve that can be met within the chemical composition limits for SAE 8620H?
   — Do the three points fall on an end-quench curve that can be met with the precision desired for SKF Steel's extra-hardenability controlled carburizing steels?

   If any of these conditions are not met, SKF Steel's technical customer services will contact the customer and try to find a solution to the specific problem encountered.
5. Once the customer requirements have been examined and found to be within the limits of what is physically possible, this specification is included in the production schedule as a separate variant.
6. The regression models will then define a steel composition which will conform to the SKF Steel extra-hardenability control specifications (32).
7. As the specific heat of steel is produced, production control computers will control the steelmaking process, and ensure that alloying and other steelmaking processes are adjusted to the composition required to meet the customer specification.

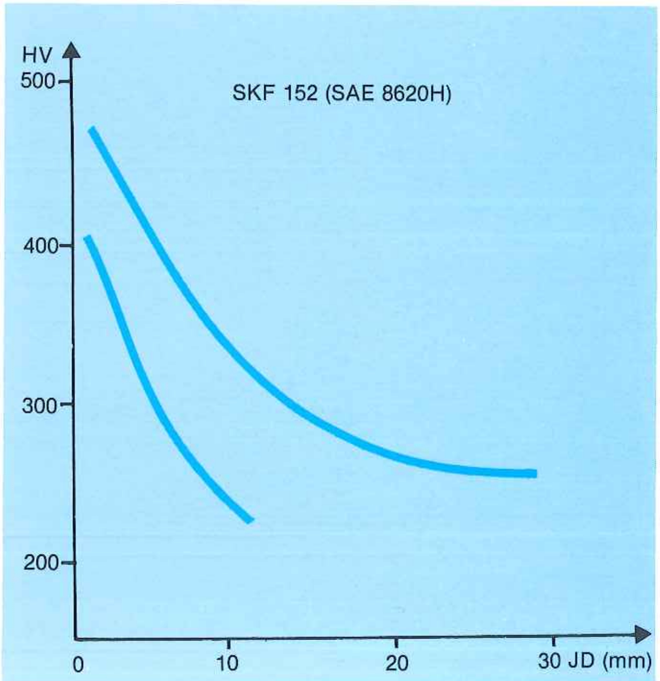

Fig. 35. H-band for SAE 8620H (based on ASTM A304).

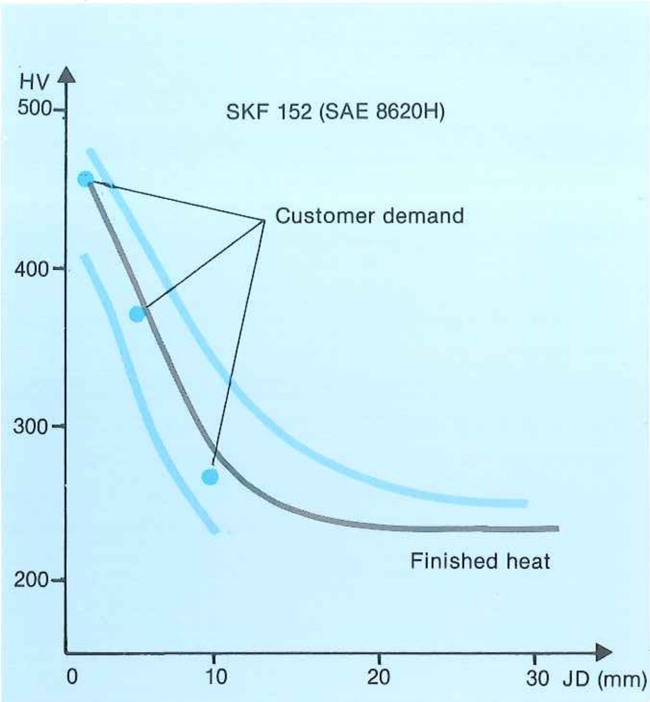

Fig. 36. Jominy-curve for finished heat.

Consequences of hardenability control

Transmission components frequently have complex geometries and thus are sensitive to warping and distortion in heat treatment.

General dimensional changes, and tendencies to distortion, are often measured by laboratory tests on samples of defined geometries. *Fig 37* shows the relationship between dimensional changes and hardness for case hardened washers. In *Fig 38* results from another type of test piece are shown, where distortion versus quenched hardness for a carburizing steel are given (8). Obviously, strict control of the core hardenability is a basic requirement if dimensional tolerances and warping are to remain predictable and be kept at a minimum.

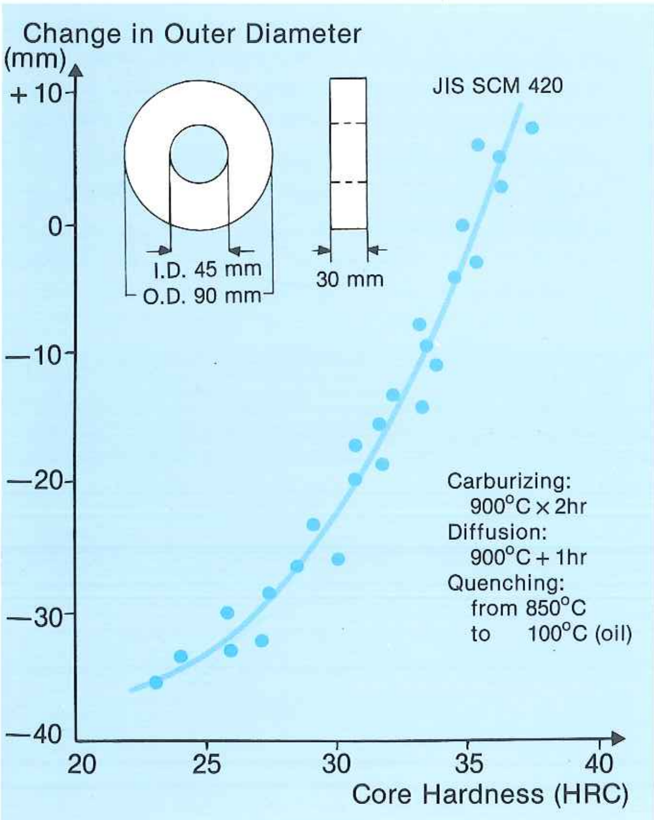

Fig. 37. Dimensional change and core hardness for a carburizing steel ~SAE 4118.
From ref. (7).

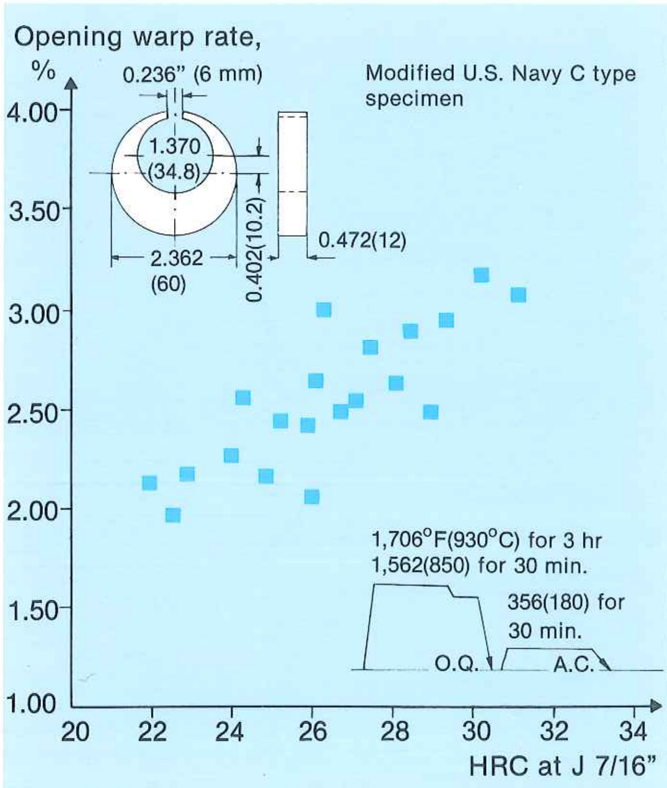

Fig. 38. Warping and core hardness for SAE 8620H standard steel. Data from ref. (8).

Conclusions

Transmission components put significant demands on the steelmaker.
Among the foremost requirements are fatigue resistance, machinability and consistency in hardenability.
Fatigue properties are determined by the oxidic non-metallic inclusion content, and consequently by the oxygen content of the steel.
Machinability is largely controlled by the content, and the morphology, of sulphide inclusions.
While sulphide inclusions do improve the machinability of steel in most applications of interest to transmission component manufacturers, sulphides only marginally affect the fatigue properties of high-hardness steel.

Sulphide morphology modification must be excersized with great care in steels of high hardness, as the modification will affect the deoxidation process. It is easy to produce steel with good machinability — to produce steel with high fatigue resistance **and** good machinability requires a combination of well designed equipment and extensive know-how.
Hardenability control is of high importance to product properties and production economy. The unique SKF Steel extra-hardenability controlled carburizing steels make it possible to define, and obtain, a steel with consistent and predictable hardenability.

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